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Citation for published version:

Gan, LK, Shek, J & Mueller, M 2014, Optimisation Sizing of Hybrid Wind-Diesel Systems using Linear Programming Technique. in *IET International Conference on Power Electronics, Machines and Drives*. IET.
<https://doi.org/10.1049/cp.2014.0469>

Digital Object Identifier (DOI):

[10.1049/cp.2014.0469](https://doi.org/10.1049/cp.2014.0469)

Link:

[Link to publication record in Edinburgh Research Explorer](#)

Document Version:

Peer reviewed version

Published In:

IET International Conference on Power Electronics, Machines and Drives

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Optimisation Sizing of Hybrid Wind-Diesel Systems using Linear Programming Technique

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Keywords: hybrid wind-diesel system, sizing, optimisation, linear programming, fixed speed wind turbine.

Abstract

Despite the great potential of hybrid wind-diesel system in supplying energy to remote or island communities, sizing the system components have been a challenging problem for many project managers due to the reliance on various factors. This work considers utilising a fixed speed wind turbine (induction generator) in the hybrid system. It requires energy for start-up operation and this work takes into account for sizing the battery storage. In addition, the trade-off between the number of batteries and diesel generator fuel usage in a system is studied. Linear programming for optimal sizing of batteries needed in a hybrid wind-diesel system, in the context of minimum diesel fuel usage is reported in this paper. Finally, this paper also shows that the storage capacity required in a hybrid system for various wind and load conditions can be computed in a systematic manner.

1 Introduction

The need for an affordable and reliable electricity supply is a major barrier to the development of many rural communities, particularly those remote from the existing electricity grid. Traditionally, off-grid systems rely solely on diesel generators, but a significant rise in oil prices has made diesel-based systems uneconomical. Renewable generation technologies allows the use of natural resources as alternative energy sources, but their intermittency typically results in inadequate energy supply for a substantial proportion of the year. However, combining renewable energy sources with conventional diesel generation and energy storage systems in so called “hybrid renewable energy systems” may provide reliable electricity supply with reduced battery storage and/or diesel requirements.

The concept of off-grid hybrid wind-diesel systems seems financially attractive and technically more reliable than the conventional stand-alone wind-power systems [1]. However, one of the main challenges experienced by project managers is the sizing of components. This challenge can be mainly attributed to the wind resource availability and load demand requirements for different sites. In addition, the stochastic nature of wind speed which leads to the unpredictability of wind resource, further adds to the challenges in its operation. Therefore, to guarantee the load demand is fully met by the hybrid system, it needs to be sized by considering the abovementioned factors.

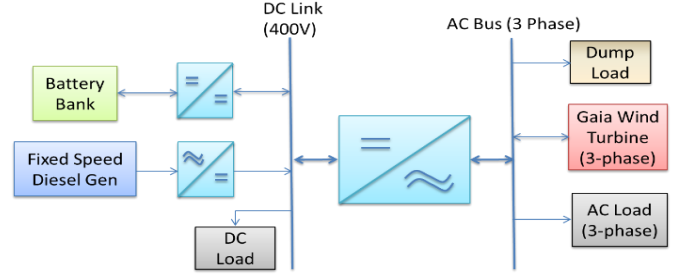


Figure 1: Mixed AC/DC System

In this work, sizing of the proposed hybrid wind-diesel system is considered as shown in Figure 1. The fixed speed operation employs squirrel cage induction generator which is well known for its robustness, high reliability, simple operation and low maintenance [2]. However, the required energy for start-up operation should be taken into consideration for system sizing in order to obtain more accurate results. From previous works, linear programming (LP) has already been utilised to optimise hybrid system components [3] [4]. However, the main focus of this paper is using LP to find the trade-offs between diesel fuel usage and storage capacity, given a fixed number of wind turbines. From a financial perspective, the cost of a wind turbine is relatively high compared with batteries or a diesel generator. Hence, this restricts the end-customer to using a minimal number of wind turbines for the system. In view of this problem, this work focuses on the batteries and the diesel generator capacity instead, as these are relatively easy to be manipulated. At this stage, the operation (power dispatch strategy) of the hybrid system is optimised with the objective of minimising the total cost of operation. The optimisation is performed with Xpress-MP software. The methodology of determining the optimised battery capacity and diesel fuel consumption is summarised in Figure 2. Wind power profile and load demand are the inputs to the model and its associated outputs are battery capacity required and diesel

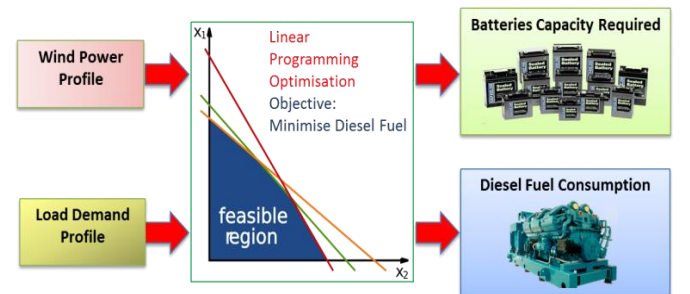


Figure 2: Modelling and simulation methodology

fuel consumption. The following section describes the wind energy profile, load profile and diesel generator cost modelling. A sensitivity analysis is carried out which is vital to increase the confidence in calculating the correct battery capacity by simulating different wind and load scenarios. Based on this, an equation for calculating the batteries needed for a particular site to smoothen the power is formulated. This equation is a function of wind power and load demand as these two parameters are the key in balancing supply and demand. Its corresponding diesel fuel consumption (when batteries and wind turbine cannot meet the demand) will also be demonstrated.

2 Modelling

In the literature, commercially available software tools (e.g. HOMER) and optimisation techniques (e.g. LP, generic algorithm, particle swarm optimisation) are commonly used to size a hybrid system. Amongst these, LP methodology is adopted in this work due to the ease of coding, despite its shortfall in computation time efficiency [5]. Most of the commercially available tools have “Black Box” code utilisation while other optimisation techniques are either relatively harder to code or lack literature examples. A comparison table summarising the advantages and disadvantages of each approach is given in [5].

LP is simply defined as a mathematical technique to find the best possible solution (such as maximum profit or minimal cost) by means of linear functions. The optimised solution is subjected to linear equality and linear inequality constraint. This section describes the mathematical modelling of the considered hybrid system with respect to matching of power generation and load demand, diesel fuel cost and battery state of charge constraints.

2.1 Wind Profile

The wind turbine’s generated power is modelled based on wind turbine power curve as shown in Figure 3. It is formulated empirically using measured wind speed and power output from the wind turbine.

Thus, the output power from the wind turbine can be computed at any given wind speed using the approximated equation. The equation is a function of wind velocity, given as:

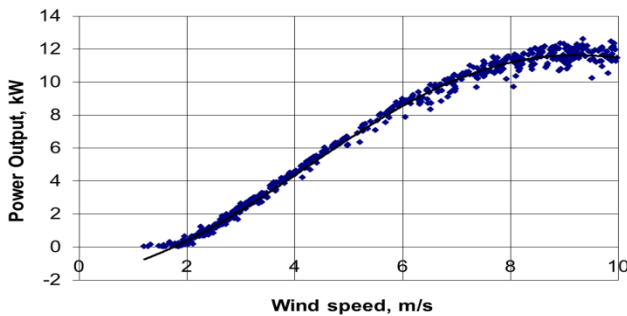


Figure 3: Wind Turbine Approximated Power Curve

$$P_{wind} = -2e^{-5}V^6 + 0.001V^5 - 0.0155V^4 + 0.0712V^3 + 0.1058V^2 + 0.7631V - 1.9152 \quad (1)$$

where:

P_{wind} : Wind Turbine Output Power (kW)

V : Wind Velocity (m/s)

It is vital to emphasise that power generation starts at wind speeds above 3.5m/s, which is the cut-in speed until the rated speed 9.5 m/s is reached. For wind speeds exceeding 25 m/s, the turbine has to be stalled to prevent structural damage [6].

The hourly wind speed used in this simulation is shown in Figure 4 and its corresponding generated output wind power is depicted in Figure 5. As observed, the wind turbine is in stall position and does not generate power when the wind speed is below the cut-in speed. This happened at hour 4, 7, 10, 13, 14 17 and 21 of the day. Note that the small negative value between hour 13 and 14 is due to the interpolation error.

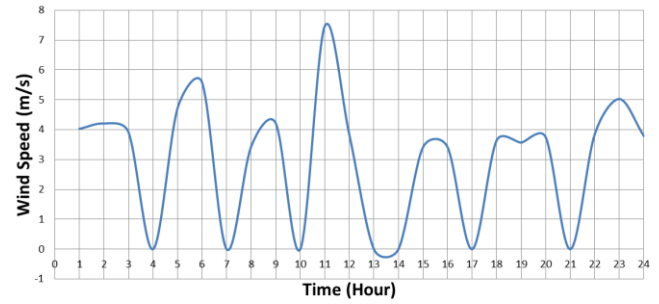


Figure 4: Typical daily average wind speed

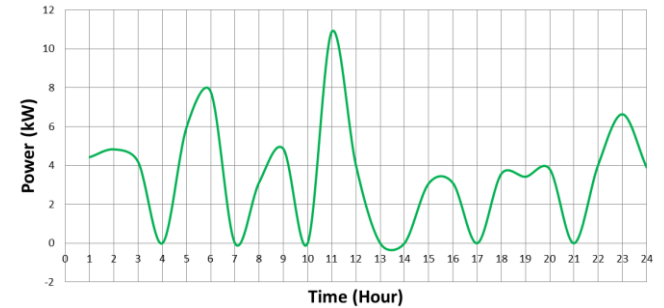


Figure 5: Output power from the wind turbine

2.2 Load Profile

The consumer load profile gives a total of 15 kWh per day. On top of that, the required start-up energy of the wind turbine (using induction generator) is given as:

$$\begin{aligned} P &= \sqrt{3} VI \\ &= \sqrt{3} \times 415 \times 100 \\ &= 71.88 \text{ kW} \end{aligned} \quad (2)$$

$$\begin{aligned} E &= Pt \\ &= 71.88 \times \frac{7.5}{3600} \\ &= 0.15 \text{ kWh} \end{aligned} \quad (3)$$

It is assumed the start-up time to take place without a soft-starter and the time required for the process to be completed is 7.5 seconds. Typically, the wind turbine start-up process will take place several times a day. This study assumes six

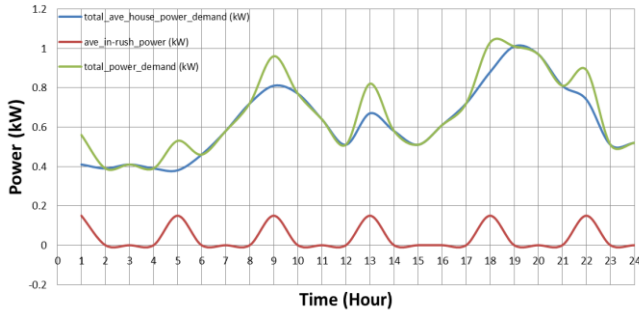


Figure 6: Load profile (consumer plus wind turbine start-up)

times of start-ups a day, distributed evenly throughout the 24 hours. Figure 6 shows the consumer, wind turbine start-up and total load power throughout the day. It can be observed that the induction generator's start-up energy is relatively significant and thus should be taken into consideration when sizing such hybrid system.

2.3 Diesel Generator Costs

Diesel generators are the most common power supply for off-grid communities. In a hybrid wind-diesel system, the diesel generators play a role in backup and supplying power deficit. While being relatively inexpensive to purchase, diesel generator sets are generally expensive to operate and maintain, especially at part-load levels.

In this optimisation problem, our objective is to minimise diesel generator usage and therefore maximise the use of renewable energy, i.e. wind energy. The fuel cost of a power system can generally be expressed as a quadratic polynomial equation, a function of its real power output [7]. The total \$/hour diesel generator fuel cost, $F_{DG,i}$, can be expressed as:

$$F_{DG,i} = \sum_{i=1}^N (d_i + e_i P_{DG,i} + f_i P_{DG,i}^2) \quad (4)$$

where N is the number of generators, d_i , e_i and f_i are the coefficients of the generator (typically given by the manufacturer), $P_{DG,i}$ is the output power of i th diesel generator. In this case, the adopted diesel generator's coefficients are taken from a Cummins 6kW diesel generator data sheet [8]. The diesel generator fuel cost coefficients for equation (4) in this case are listed as $d_i = 0.4333$, $e_i = 0.2333$ and $f_i = 0.0074$.

The approach which is utilised in this optimisation problem is LP, thus the quadratic cost function needs to be linearized using a piecewise linear cost function [9], which can then be implemented in Xpress-MP. The break points for the function are at $\frac{1}{4}$, $\frac{1}{2}$, $\frac{3}{4}$, and full load. Thus, the diesel generator is represented by "four generators" (for example: D1, D2, D3 and D4) with different marginal price at different generation levels. The computed marginal prices are gradients of each generation level. Figure 7 demonstrates the piecewise linear cost curve and its associated constant marginal cost curve is given in Figure 8.

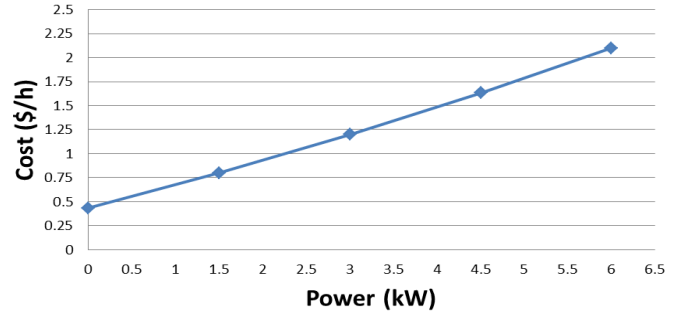


Figure 7: Cummins diesel generator piecewise linear cost curve

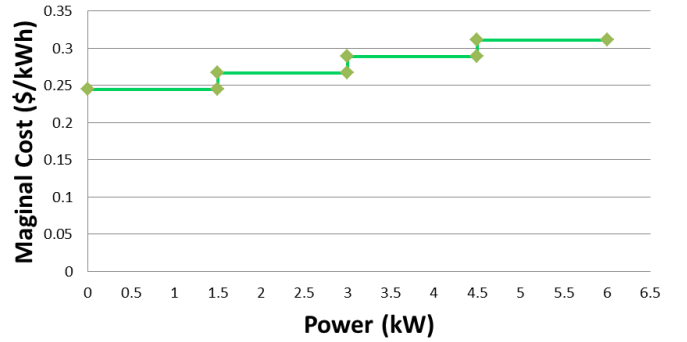


Figure 8: Cummins diesel generator marginal cost curve

3 Battery Storage Calculations

In a hybrid wind-diesel system, battery banks are electrochemical devices that store energy from other AC or DC sources for later use. The batteries serve as the platform to maximise the usage of renewable energy by storing excess energy whenever the supply from the wind turbine exceeds the load demand. Furthermore, a properly-sized battery bank is capable of reducing the number of start-stop cycle of the diesel generator and also reduce fuel consumption, compared to diesel-only operation.

When determining the state of charge (SOC) for an energy storage device, the following constraint must be satisfied.

$$SOC_{\min} \leq SOC \leq SOC_{\max} \quad (5)$$

where SOC_{\min} and SOC_{\max} are the minimum and maximum state of charge respectively. SOC_{\min} and SOC_{\max} are set at 20% and 100% of the battery capacity, respectively. It is assumed that the initial (first hour) capacity of the battery is 2 kWh at the beginning of the simulation.

During the operation of the hybrid system, the following energy-production scenarios exist:

- The energy produced by diesel generator is used to charge the batteries and supply power to the load via bi-directional converter (when low/no wind and 20% SOC).

- The surplus of energy from wind turbine (not absorbed by consumer load) is converted to DC current and is stored in the batteries via the charge controller.
- The stored energy in batteries is used to cover the energy deficit during low wind condition.

The adopted approach to size the batteries is laid out in [10]. The magnitude difference between generated power (P_{gen}) and the demand (P_{dem}) over a given period of time is:

$$\Delta P = P_{\text{gen}} - P_{\text{dem}} \quad (6)$$

The power equation can then be translated into energy generated and demanded (W_{gen} , W_{dem}) over a period of 24 hours and be written as:

$$W_{\text{gen}} = \sum_{n=1}^{24} [(\Delta T)(K_w P(n)_w)] \quad (7)$$

$$W_{\text{dem}} = \sum_{n=1}^{24} [(\Delta T)(P(n)_{\text{dem}})] \quad (8)$$

where K_w represents the number of wind turbines, n is the sampling time (hour of day), and ΔT is the time between the samples (in this case one hour).

In order to achieve the balance between generation and demand over a period of time, the curve of ΔP versus time must have an average of zero over the same time period. Note that positive values of ΔP indicate the availability of generation and negative ΔP indicates generation deficiency. The energy curve can be obtained by integrating ΔP .

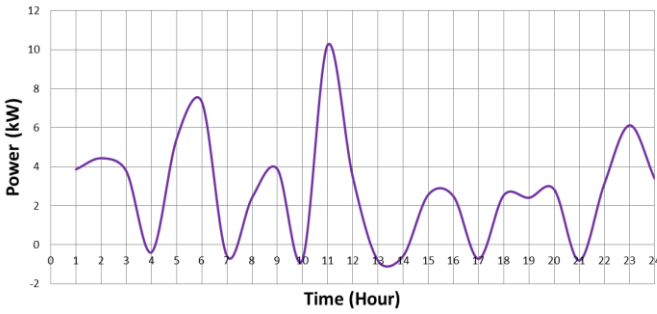


Figure 9: Average daily ΔP

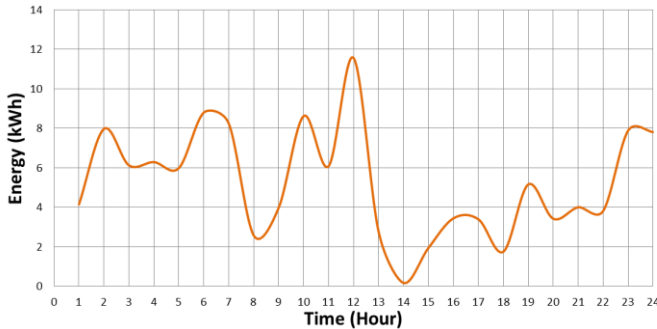


Figure 10: Average daily ΔW

$$\Delta W = \int \Delta P dt = W_{\text{gen}} - W_{\text{dem}} \quad (9)$$

The energy curve of equation (9) can be used to find the required storage capacity for the hybrid system. The ΔP and ΔW curves are depicted in Figure 9 and 10 respectively.

To simplify matters, it is important to note the following operating assumptions are made before calculating the storage required:

1. Diesel generator is still able to be switched on as long as the following constraint is met:

$$P_{\text{diesel}} + P_{\text{wind}} + P_{\text{storage}} \geq P_{\text{demand}}$$

2. The dispatch operation is optimised for the period of 24 hours, subjected to the stated constraints.
3. The accumulated excess power from the wind turbine (after supplying demand) at the end of the day is dumped at the first hour during the following day. This study does not consider accumulating the charge daily as this will require a yearly analysis for accurate sizing. Instead, this shortfall will be compensated by the sensitivity analysis which will be discussed in the next section. The sensitivity analysis will undertake the case whereby wind energy generation is balanced with the load demand over a period of 24-hours (by lowering the wind generation with a fixed demand from the case), i.e. there is approximately no surplus of energy at the end of the day.

On an average day, the battery is required to cycle its charge between the positive and negative peaks of the energy curve. Therefore, the battery should be sized at least equal to the difference between the positive and negative peaks of the energy curve, as shown in equation (10).

$$\text{Required Storage Capacity} = \text{Max} \int \Delta P dt - \text{Min} \int \Delta P dt \quad (10)$$

If the batteries are not allowed to cycle through more than 80% of their rated capacity, then the number of batteries required for the needed storage capacity is computed as:

$$\text{Number of batteries} \geq \frac{\text{required storage capacity}}{(0.8)(\text{rated capacity of each battery})} \quad (11)$$

A common battery capacity of 33Ah with 12V is used in this study, resulting in 27 batteries required for the hybrid system. This number of batteries will provide uninterrupted electricity supply to the consumer throughout the day based on the wind speed and load demand profile used. The next section explores the battery capacity required through the proposed sensitivity analysis.

4 Sensitivity Analysis

Throughout the year, the wind speed varies greatly even on a daily basis. Hence, the associated output power will be reflected accordingly. In addition, wind resource varies greatly depending on location. To be able to emulate different wind conditions in the simulation, a multiplication factor of the base wind model with a reduction step size of 0.05, starting from 1 is applied. The gradual decrease in

multiplication factor emulates the decrease in wind speed throughout the day and for different locations.

Besides varying wind conditions, there are situations where load demand changes throughout the day and seasons. Therefore, the load demand is varied with the multiplication factors linearly upwards until 3 with a step size of 0.05, repeating for each wind multiplier. By doing so, we simulate a great variety of possibilities of different wind and load conditions based on the same profile. The model is designed in such a way that unfeasible data will not be demonstrated.

Figure 11 graphically shows the optimised storage required for different wind and load demand. Most batteries are needed for the case of high wind (multiplier = 1) and low demand (multiplier = 1). This is due to the huge amount of energy excess at the end of the day. On the other hand, less batteries are needed for minimal wind and high load condition.

Figure 11 is a convenient chart for project managers to size the batteries required for a particular household. However, in order to accurately determine the amount of batteries needed for a particular site, it is convenient to derive an equation. A linear fifth order polynomial equation (Poly55) with its coefficients which represents the surface plot is listed as:

$$f(x,y) = p00 + p10*x + p01*y + p20*x^2 + p11*x*y + p02*y^2 + p30*x^3 + p21*x^2*y + p12*x*y^2 + p03*y^3 + p40*x^4 + p31*x^3*y + p22*x^2*y^2 + p13*x*y^3 + p04*y^4 + p50*x^5 + p41*x^4*y + p32*x^3*y^2 + p23*x^2*y^3 + p14*x*y^4 + p05*y^5$$

Coefficients (with 95% confidence bounds):

p00 = -2.784 (-59.15, 53.58)	p31 = -2.785 (-33.52, 27.95)
p10 = 14.99 (-137.4, 167.4)	p22 = -56.89 (-106.3, -7.427)
p01 = 25.97 (-57.57, 109.5)	p13 = 258.7 (171, 346.4)
p20 = -15.29 (-177, 146.5)	p04 = -23.82 (-226.6, 178.9)
p11 = -94.07 (-236.8, 48.63)	p50 = -0.07832 (-2.252, 2.095)
p02 = 381.8 (226.9, 536.7)	p41 = 2.956 (-0.8029, 6.715)
p30 = 7.991 (-76.3, 92.29)	p32 = -14.85 (-22.19, -7.519)
p21 = 30.11 (-67.39, 127.6)	p23 = 64.93 (50.13, 79.73)
p12 = -56.16 (-188.3, 75.98)	p14 = -172.9 (-203.8, -142)
p03 = -334.4 (-566.9, -101.9)	p05 = 90.06 (16.71, 163.4)
p40 = -1.327 (-22.91, 20.25)	

$f(x, y)$ = Storage required
 x = Load multiplier
 y = Wind multiplier

Goodness of fit:

SSE: 1082
R-square: 0.9981
Adjusted R-square: 0.998
RMSE: 1.179

Interestingly from Figure 11, it is not a smooth or linear trend especially for the low storage region. Hence, it can be proved that the optimised storage calculations are not solely based on the availability of wind resource and load demand, but also the system operation (power dispatch strategy). Figure 12 shows the zoom version of this uneven region. It can be observed that the values are random at a certain degree. This detailed analysis is vital as the cost of batteries is heavily reflected in the total system cost.

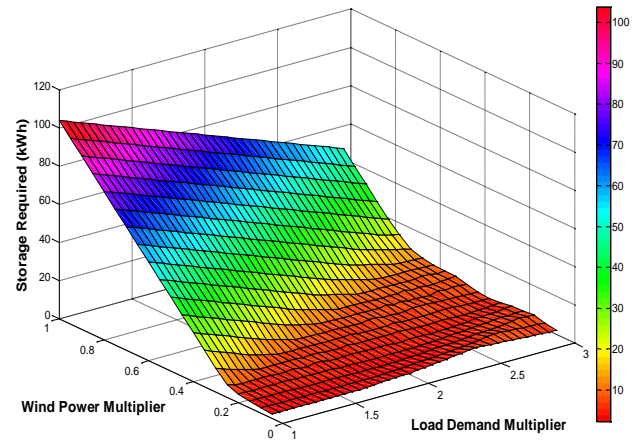


Figure 11: 3D plot of optimised storage for various wind and load condition

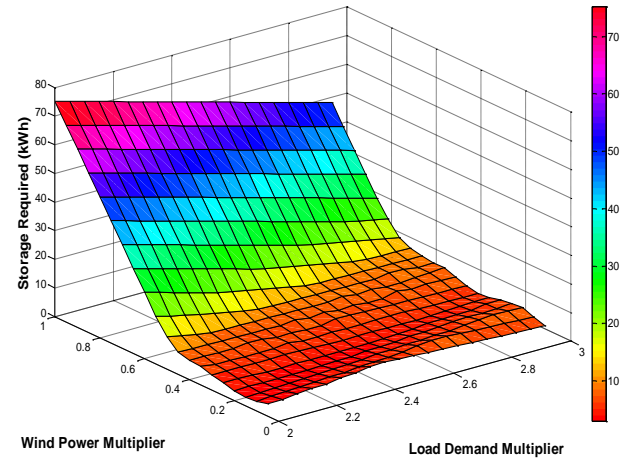


Figure 12: Zoom in version of Figure 12 (with only load demand multiplier of 2 to 3)

The corresponding daily diesel fuel cost with varying wind and load demand is plotted in Figure 13. For the case of high wind penetration and low load demand, the diesel fuel usage is zero and sufficient amount of wind power is being stored in batteries for backup. The diesel fuel cost gradually rises with lower wind and higher demand scenarios. Comparing Figure 11 and Figure 13, it is clear that there is a design trade-off between the installed batteries and diesel fuel cost.

To demonstrate the power flow from each element in the hybrid system over 24 hours, Figures 14 and 15 show the operation where the wind multiplication factor is 1 and 0.2 respectively. In Figure 14, the diesel generator was never turned on due to high wind penetration throughout the day and sufficient battery capacity to store the excess energy. However, this scenario requires a high storage capacity. In Figure 15 it can be observed that the batteries are now storing less energy throughout the day as the wind energy is reduced.

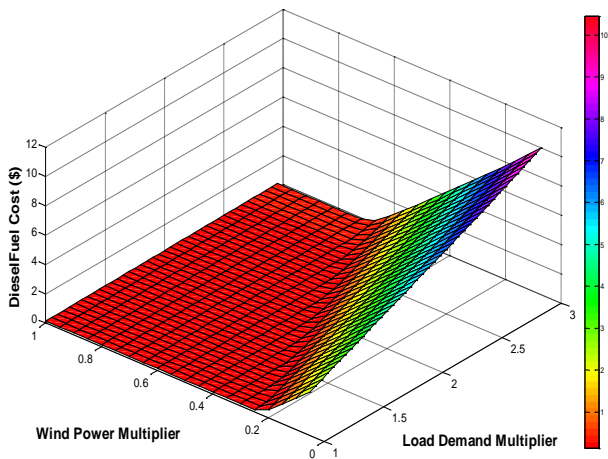


Figure 13: Optimised (minimum) diesel generator fuel cost for various wind and load conditions

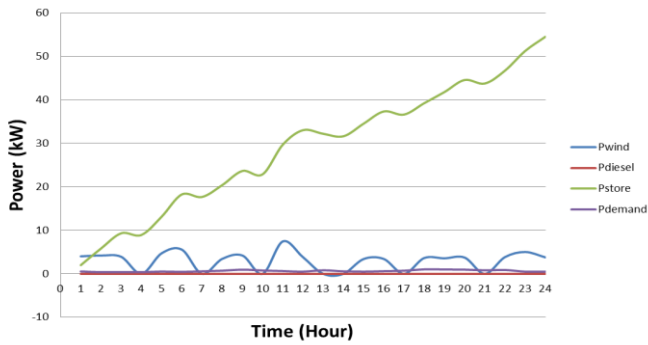


Figure 14: Operation of hybrid system with multiplication factor of 1

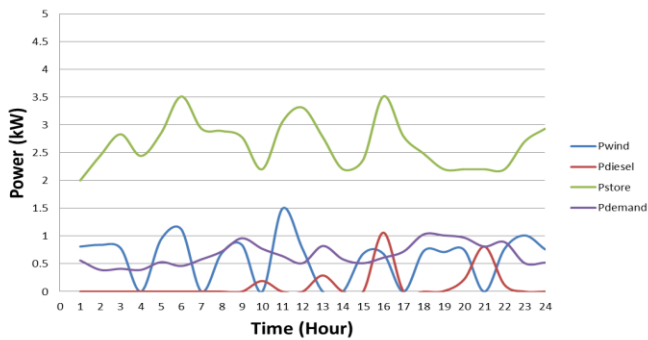


Figure 15: Operation of hybrid system with multiplication factor of 0.2

5 Conclusion & Future Work

In this study, the sizing of a hybrid wind-diesel system using LP was demonstrated. In order to determine the optimal storage capacity required for a hybrid system in different wind and load demand conditions, the formulated polynomial equation is able to provide the solution numerically. The proposed sizing methodology is suitable to be applied in various hybrid system configurations and can be extended to yearly meteorological and load demand data instead of using

24 hours data as shown in this work. In addition, more constraints such as diesel generator's greenhouse gases emission can be incorporated into the model.

Acknowledgements

The author would like to thank the Energy Technology Partnership for financial support through their Energy Industry Doctorate programme.

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